ENERGY MANAGEMENT STRATEGIES FOR COMBINED HEAT AND ELECTRIC POWER MICRO-GRID

by

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The increasing energy production from variable renewable energy sources such as wind and solar has resulted in several challenges related to the system reliability and efficiency. In order to ensure the supply-demand balance under the conditions of higher variability the micro-grid concept of active distribution networks arising as a promising one. However, to achieve all the potential benefits that micro-grid concept offer, it is important to determine optimal operating strategies for micro-grids. The present paper compares three energy management strategies, aimed at ensuring economical micro-grid operation, to find a compromise between the complexity of strategy and its efficiency. The first strategy combines optimization technique and an additional rule while the second strategy is based on the pure optimization approach. The third strategy uses model based predictive control scheme to take into account uncertainties in renewable generation and energy consumption. In order to compare the strategies with respect to cost effectiveness, a residential micro-grid comprising photovoltaic modules, thermal energy storage system, thermal loads, electrical loads as well as combined heat and power plant, is considered.

Key words: *thermal storage system, flexible operation, micro-grid, mixed integer linear programming, grid-connected mode, model based predictive control*

Introduction

In accordance with the global energy and climate objectives aimed at reducing energy generation impact on the environment, growing deployment and utilization of renewable energy sources has become inevitable. Moreover, it is assumed that the use of renewable energy sources (sun and wind in particular) in the power sector will continue to rise in the coming years. Compared to traditionally utilized, centralized power plants, renewable sources are smaller-scaled and much more geographically dispersed. In order to reduce distribution losses and to ensure reliable and secure energy supply, exploitation of the other generators sited close to place of consumption (known as distributed energy resources – DER) has also highly increased. These are primarily cogeneration power plants which can utilize natural-gas for both electricity and heat production, but can also use other renewable or low-carbon fuels such as biofuels, biogas, sewage gas etc. Considering all mentioned changes in the power sector, several challenges related to the system reliability and efficiency arise. To get insight, energy production from the renewable energy sources such as wind and sun is highly variable since it depends on the current weather conditions. In order to cope with the new conditions

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successfully, the micro-grid concept of distribution networks arising as promising one, not only in isolated and remote areas but also in urban communities [1]. Additionally, micro-grids enable some other important benefits as they can change the role of the end-users in electricity systems from the passive to the active one. Popović *et al.* in [2] define some business processes in distribution networks as well as key elements that should be (re)defined in order to enable the goal of smart grid concept.

Given the fact that the issue of reliable operation management is vital to achieve all the potential benefits that micro-grid concept offer, optimal control techniques for energy management and control of micro-grids are highly investigated in the literature [1]. There are numerous reported approaches to the dispatch problem of micro-grids, which has been studied for two operating modes: grid-connected and stand-alone (islanded) [1]. When operation is non-autonomous objective function is usually set to maximize overall profit. In addition to the economic criteria some studies also consider environmental criteria, by including optimization objective function set to minimize the CO_2 equivalent emissions which leads to multi-objective optimization problem. Although the objective of the published works is generally similar, they differ in the used techniques and micro-grid system configuration. Some of them deal with the problem by using exact optimization techniques while the others use heuristic and priority rules. The detailed information on approaches and methods applied to the planning, energy management and control of micro-grids can be found in [1, 3]. Given the fact that errors in forecasting can have significant implications on operation efficiency, short-term load and renewable generation forecasting (which refers to forecasting from one to several days ahead) play an important role in optimization of micro-grid operation [4]. Mixed integer linear programming (MILP) is widely recognized as one of the best suitable solutions to the dispatch problem and it has been used in the literature for different micro-grid configurations. Tenfen and Finardi in [5] used deterministic MILP approach to develop mathematical model for the energy management problem of micro-grids. MILP coupled with model based predictive control scheme (MPC) can bring additional benefits to the operation efficiency as it enables taking into consideration uncertainties in energy consumption or renewable generation. A considerable number of studies have already shown that the MILP coupled with MPC can provide a good solution to the optimal operation scheduling problem. Holjevac *et al.,* in [6], investigated the influence of micro-grid components on its ability to operate independently from the external grid. Therefore, deterministic model using MILP was established to simulate the combined heat and electrical power micro-grid operation over one year period. The model was further expanded with a model predictive control approach to compensate forecast errors. It has also been shown that the MPC strategy achieves the operational cost reduction. Kriett and Salani in [7] presented MILP model identifying the minimum cost operating schedule for a residential micro-grid as well as two benchmark models that reveal the value of demand side management and optimal storage control. The MILP unit commitment problem over one year was embedded in a model predictive control scheme as it was found too large to be solved in a single MILP problem. Perković *et al.* in [8] used receding horizon model predictive control for management of micro-grid that comprises renewable generators, electrical energy demand as well as storage system and plug-in vehicles. Optimal scheduling of battery for minimizing operational costs of micro-grid containing consumer, wind turbine and battery is presented by Prodan and Zio in [9]. In this work a predictive control scheme is also used to take into account uncertainties. Two-stage stochastic programming approach for micro-grid management incorporated in a model predictive framework is used in [10] by Parisio to compensate uncertainties due to fluctuating demand and generation from renewable energy sources though the feedback mechanism. The simultaneous management of energy production and energy demand with a reactive scheduling of electrical power micro-grid is shown in [11] by Silvente *et al.* Another MPC based strategy for micro-grid operation is shown in [12] by Zhang *et al.* Authors has also discussed three other strategies for evaluation of the proposed MPC based strategy. Gambino *et al.* in [13] developed MILP-MPC based algorithm for the micro-grid operation problem and applied it to a tertiary site micro-grid, located in Finland. In addition, the proposed algorithm was compared with a heuristic algorithm. An optimization model of the energy management system for a micro-grid system in Taiwan was developed in [14] by Chen *et al.* and sensitivity analysis was used to examine various scenarios for investment in local power generators and storage capacity.

The focus of this work is to estimate potential savings when strategy for operation of coupled thermal and electric power micro-grid is based on model predictive control approach that enables taking into account future predictions when making decision on system operation at the current time step. To assess possible savings, the scheduling horizon is extended to one week, and several weeks, typical for each season of the year, are considered.

Micro-grid configuration

Micro-grid configuration, shown in fig. 1, was designed in accordance with the energy requirements of a hypothetical medium-size district that has around 4,000 inhabitants (105 multi-family houses with an average of 12 apartments).

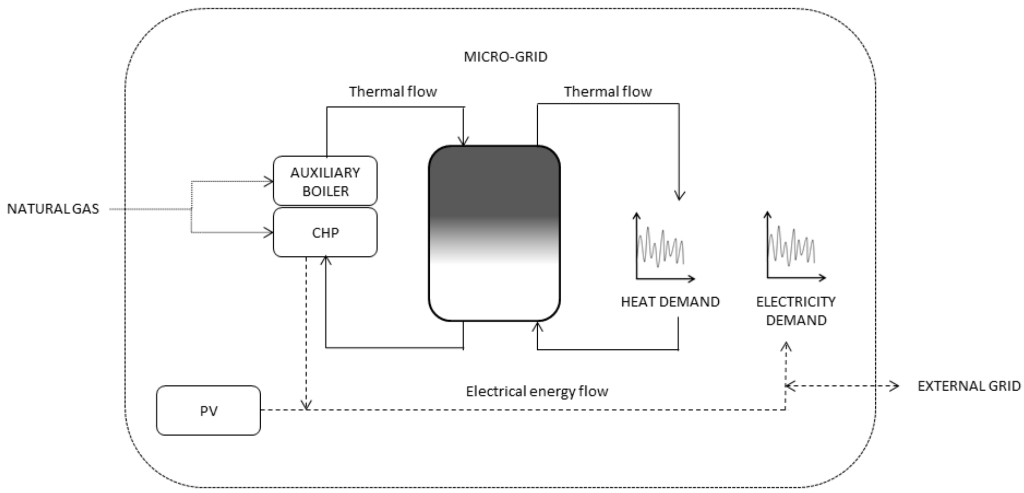

Figure 1. Residential micro-grid configuration

The micro-grid presented in fig. 1 will be used later for the evaluation and quantitative comparison of the micro-grid operation strategies presented in the next section. The each system component dimensioning is elaborated in more detail below.

Residential energy requirements usually include both electricity and heat, and thus a combined heat and electric power micro-grid is considered. Load profiles estimation for the period of one year was carried out by adjusting the reference load profiles, defined in the standard [15]. Therefore, hourly temperature and cloud cover data for the city of Zagreb were used and the procedure was taken from [16]. Firstly, load profiles for the individual multi-family house were developed. As the considered micro-grid consist of 105 multi-family houses, each with an average of 12 apartments, micro-grid load profiles were derived by summing the individual load profiles. The obtained consumer load profiles as well as annual load duration curves are shown in fig. 2.

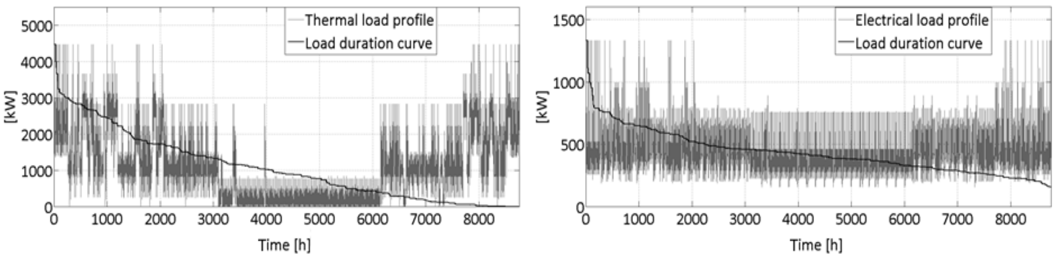

Figure 2. Thermal and electrical load profiles over one year

The coupling between different energy networks that supply the same area is enabled by a cogeneration plant located at the district heating station. To increase the ability of micro-grid components to provide flexibility the selected CHP technology is based on gas fired internal combustion engine that can change its output power relatively fast. The thermal load duration curve (shown in fig. 2) was used for the cogeneration plant sizing as it clearly represents the duration of certain load levels during the one year period. As it can be noticed in the fig. 2, the peak loads occur very rarely and only last a few hours per year. The most common thermal load ranges from 40% to 60% of the annual peak load. Consequently, the selected cogeneration plant has a maximum thermal output of 2,446 kW (which is about 55% of the peak load) and a maximum electrical output of 2,378 kW. The overall efficiency of fuel conversion is 87.1%, while thermal and electrical efficiencies are 44.2% and 42.9% respectively.

In order to ensure required amount of the thermal energy, especially during the peak hours, the system is further equipped with an auxiliary gas boiler. The boiler maximum output power is 2,050 kW which is slightly greater than the difference between the annual peak load and the CHP maximum thermal output. The auxiliary boiler overall efficiency of fuel conversion is 85%.

The key component of the system, from the viewpoint of flexibility, is a thermal storage system which can take the role of both “producer” and “consumer”, depending on the current conditions. The selected thermal storage system technology is the thermocline system using water as storage media, as it is cost-efficient and prevalent configuration for thermal energy storage technologies [17]. The thermal storage system capacity was determined according to recommendations given in [18] that addresses the problem of CHP and a thermal store optimal sizing. The report presents, inter alia, coherence between CHP-unit capacity and thermal store volume. The selected volume of the thermal storage tank is 200 m^3 and the water temperature difference is assumed to be 30 °C.

Renewable generators in the system are photovoltaic modules (PV) whose overall installed power capacity is 1,070 kW. The total area covered by the photovoltaic modules is 10,700 m^2. The photovoltaic module performance is highly affected by the weather, especially the solar irradiance and the PV module temperature. To estimate a profile for the PV generator output, the meteorological data for the location of the City of Zagreb, Croatia as well as the manufacturers’ data for the PV modules were used as model input. The calculation method is adopted from [19] and profiles of generator power output over a winter week, summer week, and week in the transitional period are obtained.

The electricity demand is partially met by photovoltaic modules installed on the roofs of buildings. The rest of this demand is covered by CHP or by electrical energy imported from the external grid. The micro-grid operates in parallel with an external grid and thus surplus electrical energy can be exported as well.

The estimated investment cost for the production plants is 5,600,000 €. Investment in the CHP unit is the major contributor representing 45% of total estimated investment cost, while the auxiliary boiler and photovoltaic modules shares are around 26% and 29% respectively. The estimated investment cost for the thermal storage system is around 100,000 €.

Energy management strategies formulation

In order to formulate energy management strategies that can ensure energy balance at each time step and provide the cost-efficient operation of the micro-grid a mathematical description of the system is used. The mathematical model comprises energy balance equations as well as inequalities that arise from the operating ranges and technical specifications of the micro-grid components. To ensure the overall energy balance at each time step over scheduling horizon NS, considering production, consumption, interaction with the external grid (import and export of electricity) as well as the charge and discharge of the thermal storage system, thermal and electrical energy balance equations are formulated as follows:

$$\sum_{p=1}^{2} HG_{p,k} + HS_k - HD_k - HS_{k+1} = 0 \quad \forall k \in \{1,2,..., NS\} \tag{1}$$

$$\sum_{p=1}^{2} EG_{p,k} + ER_k \pm EE_k - ED_k = 0 \quad \forall k \in \{1,2,..., NS\} \tag{2}$$

In order to mathematically describe constraints that indicate the operating ranges of the manageable system components, following inequalities are used:

$$\left\{HG_{p,k} \in \mathrm{R} \mid HG_{p,k}^{\min} \le HG_{p,k} \le HG_{p,k}^{\max}\right\} \ \forall p,k \in \{1,2,..., NS\}, \text{ if generator on} \tag{3}$$

$$HG_{p,k} = 0 \ \forall p,k \in \{1,2,..., NS\}, \text{ if generator off} \tag{4}$$

$$\left\{HG_{p,k} \in \mathrm{R} \mid HG_{p,k}^{\min} \le HG_{p,k} \le HG_{p,k}^{\max}\right\} \ \forall p,k \in \{1,2,..., NS\}, \text{ if generator on} \tag{5}$$

$$HG_{p,k} = 0 \ \forall p,k \in \{1,2,..., NS\}, \text{ if generator off} \tag{6}$$

$$0 \le HS_k \le HS^{\max} \ \forall k \in \{1,2,..., NS\} \tag{7}$$

Due to the characteristic feature of gas engines that they can change its power output relatively fast, the ramp constraints are not taken into account. To pose the overall optimization problem, the objective function, that expresses the aim to maximize profit (or minimize loss) of the micro-grid operation have to be added. The present paper proposes several management strategies that mainly differ in the way the objective function is formulated. The first strategy (further denoted as S1) is a linear optimization based strategy with an additional rule. It takes into account only the present state and do not uses the forecast data of renewable generation or load demand in the following period. The second strategy (further denoted as S2) also considers just the actual state of the system but it is based on pure optimization approach as the energy management problem is stated as a mixed integer linear programming problem. Unlike the previous strategies, the third strategy (further denoted as S3) is formulated taking into account predictions on the future consumption and renewable generation. Each of the strategies is based on the above equations and explained in more detail below.

Strategy S1

Linear programming is an optimization method suitable for solving problems in which the objective function and the constraints appears as linear function of the decision variables [20]. In the present optimization problem, controllable components of the system are represented by decision variables while energy production from the photovoltaic modules and the consumption at each time step, as well as the technical specifications of the system components, determine equality and inequality constraints. However, technical minimum of the CHP plant is about 20% of the maximum output power and thus the generator operating range is not continuous and depends on whether is the plant turned-off or on. The decision on the generator on/off state can be included into the optimization problem by adding the binary variable, but it causes the energy management problem becomes a problem of mixed integer linear programming. As an alternative to the use of mixed integer linear program, that is much harder to solve than linear program, the strategy S1 proposes the introduction of an additional rule that defines the generator on/off state as shown by eq. (8):

$$\text{CHP}\begin{cases}\text{on}, & HD_k + HS^{\max} > HG_{2,k} + HS_k \quad \forall k \in \{1,2,\ldots,NS\} \\ \text{off}, & \text{otherwise}\end{cases} \tag{8}$$

As it can be seen from eq. (8), the cogeneration plant is turned-off only if the sum of the stored thermal energy and the minimum possible amount of produced thermal energy in an hour (determined by CHP minimum stable operating level) is greater than the sum of the maximum thermal storage system capacity and the thermal energy consumption. Otherwise, it is turned-on. The rule thus affect the number of decision variables in the objective function, which is in the case of strategy S1 given by eq. (9):

$$\min\ f = \begin{cases}\displaystyle\sum_{p=1}^{P}\frac{HG_{p,k}}{\eta_{Tp,k}} \times g_k \pm EE_k e_k - HS_{k+1} \times g_k \quad \forall p,k \in \{1,2,\ldots,NS\}, \text{ if CHP on} \\ \dfrac{\text{HG}_{2,k}}{\eta_{T2,k}} \times g_k \pm EE_k \times e_k - HS_{k+1} \times g_k \quad \forall k \in \{1,2,\ldots,NS\}, \quad \text{if CHP off}\end{cases} \tag{9}$$

Strategy S2

Unlike the previous strategy, the strategy S2 involves the decision on when the cogeneration unit should be started and stopped in optimization problem. This is made by adding binary variable X_k and thus the overall optimization problem is stated as a mixed integer linear programming optimization problem. Instead of using the constraints given by eq. (3) and (4) as well as eq. (5) and (6), the strategy S2 uses the constraints given by eq. (10) and (11), that include binary variable which indicate if generator is being used or not:

$$\{HG_{p,k} \in \text{R} \mid X_k \times HG_{p,k}^{\min} \le HG_{p,k} \le X_k \times HG_{p,k}^{\max}\} \ \forall p,k \in \{1,2,\ldots,NS\} \tag{10}$$

$$\left\{EG_{p,k} \in \mathrm{R} \mid X_k \times EG_{p,k}^{\min} \le EG_{p,k} \le X_k \times EG_{p,k}^{\max}\right\} \; \forall p,k \in \{1,2,..., NS\} \tag{11}$$

The above objective function is therefore subjected to the equality constraints given by eq. (1) and (2) and inequality constraints given by eq. (7), (10) and (11):

$$\min \; f = \sum_{p=1}^{P} \frac{HG_{p,k}}{\eta_{Tp,k}} \times g_k \pm EE_k \times e_k - HS_{k+1} \times g_k \quad \forall k \in \{1,2,..., NS\} \tag{12}$$

Strategies S1 and S2 do not take into consideration electricity prices, predicted consumption and generation profiles in the coming periods when making a decision on the system operation at the current time step. Therefore, if the current electricity price is greater than the natural gas price, the CHP operates at maximum possible output power and the thermal storage system is charging. This may have negative influence on the system operation efficiency in the coming period when the electricity market conditions are even more favourable.

Strategy S3

The present strategy has been developed to cope with the problems that arise from the previous approaches. For this purpose, a look-ahead approach that uses forecasted loads and generator profiles as well as market price profiles for a whole scheduling horizon can be applied when formulating objective function. However, if the energy management problem is formulated as a single MILP problem for a longer scheduling horizon (*e. g.* a week or a year), the optimization problem becomes computationally intensive and the solution quality is strongly dependent on the forecast accuracy. Therefore, some elements of the model based predictive scheme are used as a solution method as it can compensate for any disturbances that may act on the system. In the case of strategy S3, the scheduling horizon is divided in a finite number of time intervals (hours). At the current point in time, an objective function and constraints are formulated for the period n_p (prediction horizon) based on predictions of the renewable generator production and consumption. The prediction horizon is set to 24 hours and the control horizon is one hour which means that optimization problem is solved for 24 hours but only the solutions related to the current hour are implemented and the prediction horizon is shifted. At the next time step, a new optimization problem is solved using new information and the whole procedure is repeated throughout the whole scheduling horizon.

The objective function for each prediction horizon, which is subjected to the constraints given by eqs. (1, 2, 7, 10, 11) is given by eq. (13):

$$\min \; f = \sum_{s=0}^{NP-1} \left(\sum_{p=1}^{2} \frac{HG_{p,k+s}}{\eta_{Tp,k+s}} \times g_k \pm EE_{k+s} \times e_{k+s} - HS_{k+s} \times g_k \right) \; \forall k \in \{1,2,..., NS\} \qquad s \in \{1,2,..., NP-1\} \tag{13}$$

Simulation results

In order to test and compare the proposed strategies, simulations of the micro-grid operation over a typical winter week, summer week and a week in the transitional period were performed and the results are presented below. To provide the evolution of the electricity prices on the electricity market historical data on the wholesale market prices were taken from [21]. These data were used to create the normalized curve which was further multiplied by an average electricity price for the end users in the Croatia. In the present case, the natural gas price is assumed to be constant. To test and compare the proposed strategies, simulations of the micro-grid operation over a typical winter week, summer week and a week in the transitional period were performed and the results are presented below.

Simulations of the system operation in the winter week are presented in fig. 3. During the winter period the cogeneration plant usually operates at maximum output power level due to high thermal energy demand. In addition, the annual peak loads are very common at this time of the year.

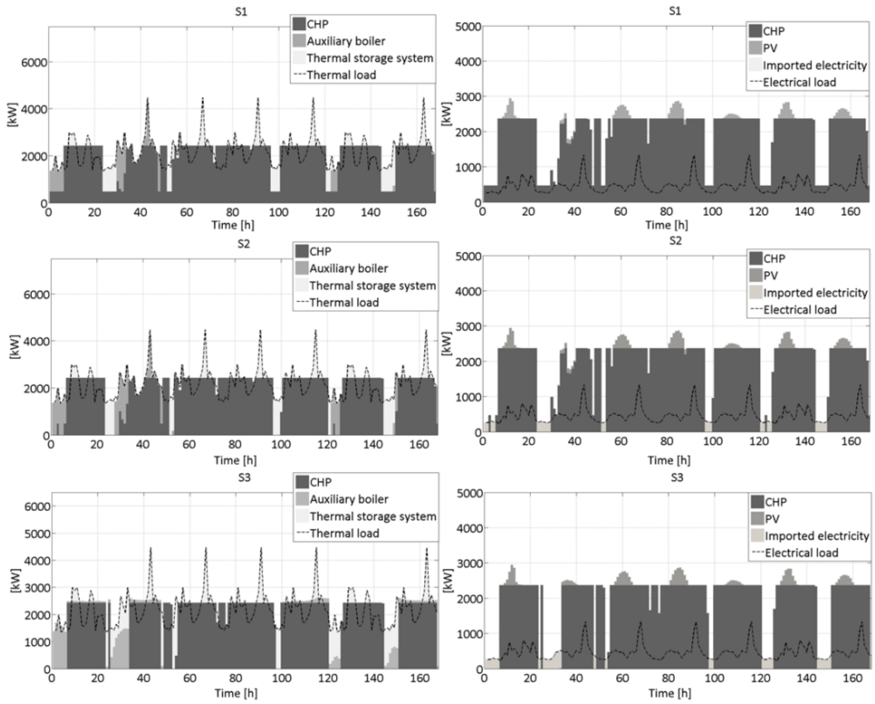

Figure 3. Thermal and electrical energy (winter week)

In the case of strategy S1, the cogeneration plant is continuously in the operation at least at a minimum output power level (technical minimum) even when electricity prices are extremely low and the demand can be covered by the stored thermal energy (fig. 3). This is due to the condition which does not allow the cogeneration plant to come out of operation, if the thermal storage system is not fully charged. Contrary, in the case of strategy S2, the CHP plant is turned-off when the electricity price is lower than the price of the natural gas and, at the same time, the heat demand can be met by the other system components. The micro-grid operation during the winter week, based on strategy S3, does not differ significantly from that in the case of strategy S2. This is due to high thermal loads, which leads to frequent charging and discharging of the thermal storage system. It can be concluded that the longer prediction horizon (MPC approach) does not change the system operation considerably in the winter week. The auxiliary boiler is mainly used for the peak loads or when electricity price is lower than the price of natural gas. As it can be seen in fig. 3, during the winter period a large amount of the produced electricity is exported to the main grid as the cogeneration plant often operates at the maximum output power level. In the case of strategies S2 and S3 the small amount of electricity is imported while in the case of strategy S1 electricity import is completely absent.

The simulations of the system operation during the week in the transitional period, presented in fig. 4, clearly show the differences among proposed strategies.

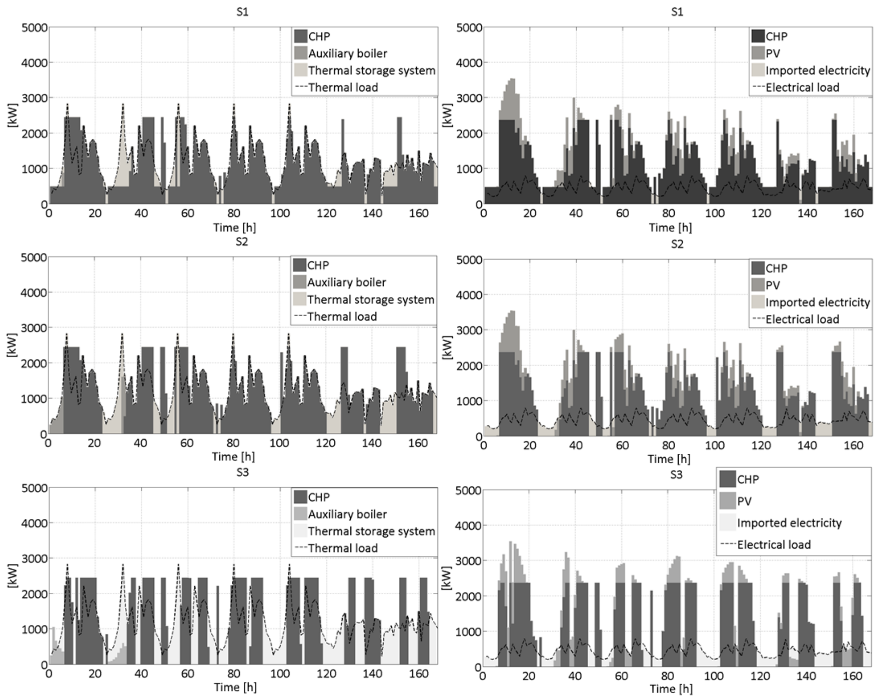

Figure 4. Thermal and electrical energy (week in transitional period)

Thermal energy consumption during the week in the transitional period is usually considerably lower than the consumption in the winter period which results in the larger quantities of stored energy, especially in those hours when CHP operates at high output power level. In the case of strategy S1, the cogeneration plant is very often in the thermal load following mode and rarely comes out of operation. It occurs because of the condition that forces CHP to operate at the output power level which is greater than the current thermal load level, if the storage system is not fully charged, in spite of the current market conditions. In the case of strategy S2, the CHP operating mode is similar, but slightly better adapted to the electricity market conditions (CHP is out of operation when the electricity price is lower than the price of the natural gas). Micro-grid operation based on strategy S3 is completely different from the system operation in the previous cases. The cogeneration plant is quite seldom in the operation but it usually operates at its maximum output power level when electricity market prices are high. The auxiliary boiler is only used at the beginning of the scheduling horizon when there is a deficit of the stored thermal energy. In the case of strategy S1 (fig. 4) due to the significant local generation, electrical energy is almost not imported. However, electrical energy is generated when the electricity market prices are low and in fact, the local generation is not profitable. On the contrary, in the case of strategy S3, relatively large amount of the electrical energy is imported but also the exports are considerable, particularly when the market prices are high. Finally, such a mode of the operation results in the higher cost-efficiency of the system operation during the week in the transitional period.

Simulations of the system operation during the week in the transitional period point out that the strategies which do not consider the expected consumer load profiles, market price profile as well as the forecasted renewable generation in the following hours, cannot provide the cost-efficient system operation through the whole week.

As can been seen in fig. 5, the described problem is even more noticeable when the micro-grid operates in the summer week.

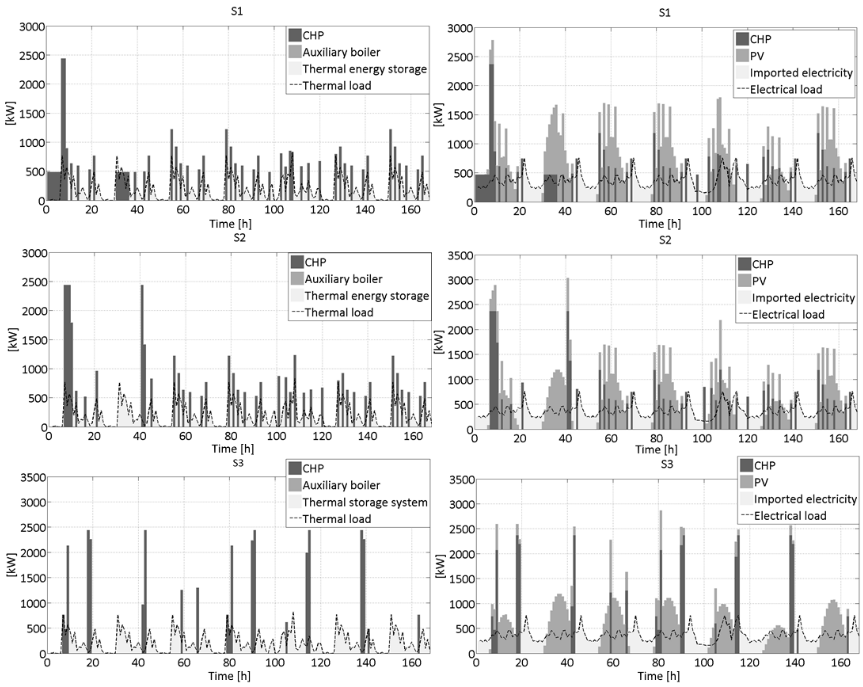

Figure 5. Thermal and electrical energy (summer week)

This is caused by the low thermal loads (fig. 5), which further causes the storage system to be fully charged after just a few hours of the CHP operation at the maximum output power (it occurs at the beginning of the week). Thus, in the coming hours, the cogeneration plant must be out of operation (or in the load following mode) in spite of the high electricity prices. When compared with the strategies S1 and S2 strategy S3 is much more suitable for the system operation during the summer, as it enables the CHP operation at the maximum output power level when the peak electricity prices occur. In addition, electrical energy production from the renewable generator is significant in the summer period due to high values of the solar insolation, particularly in the middle of the day. That ensure the large incomes which leads to the higher operation cost-efficiency.

The quantitative comparison of the proposed strategies is presented in tab. 1. Therefore, the incomes and expenses as well as the total profit per week, in the case of each strategy, are presented. Additionally, the savings relative to strategy S1 were accounted and presented in tab. 1. As it can be noticed, in the case of the operation during the winter week, the relative savings are quite low. The relative saving in the summer week is the most significant and in the case of strategy S3 it is almost 90%. It is worth mention that the absolute savings are not negligible, even in the case of the system operation during the winter week, which ultimately may affects the overall annual profit (or loss).

Table 1. Comparison of the proposed strategies for micro-grid operation in the grid connected mode

		Strategy S1	Strategy S2	Strategy S3 (no forecast error)
Revenue (A)	Winter week	18,502.0 €	18,444.0 €	18,720.0 €
	Week in the transitional period	11,273.0 €	11,820.0 €	12,520.0 €
	Summer week	4,160.2 €	4,437.5 €	4,344.9 €
Expense (B)	Winter week	31,600.7 €	31,344.2 €	31,545.8 €
	Week in the transitional period	18,368.4 €	18,343.8 €	18,483.4 €
	Summer week	4,836.8 €	4,902.9 €	4,427.0 €
Total profit per wek (A)-(B)	Winter week	−13,098.7 €	−12,900.2 €	−12,825.0 €
	Week in the transitional period	−7,095.4 €	−6,523.9 €	−5,963.5 €
	Summer week	−676.2 €	−465.4 €	−82.08 €
Savings (S1-S2)/S1 (S1-S3)/S1	Winter week		1.5%	2.1%
	Week in the transitional period		8%	16%
	Summer week		31.17%	87.1%

The comparison presented in tab. 1, assumes the perfectly accurate forecasts of the consumption and renewable generation in the case of strategy S3. Given the fact that this is an "ideal case" and forecast errors are common, especially at the end of the prediction horizon, strategy S3 is further tested taking into account the forecast uncertainty. Therefore, new load and renewable generator profiles have been formulated to obtain new inputs for prediction horizon at each time step. The new load profiles and renewable generator profile have been obtained by reshaping the reference profiles, using normal distribution with linearly increasing standard deviation according to [6]. Thus, the largest forecast errors occur at the end of the prediction horizon. The largest deviation from the reference load profile is set to 20% while the largest generation forecast error is 40%.

As expected, the simulation results (shown in tab. 2) indicate that if there are errors in the forecasts for the prediction horizon, the losses in the typical weeks are greater than in the "ideal cases" (when the forecasts for the prediction horizon are perfectly accurate).

Table 2. Profit per week in the case of strategy S3 ("ideal case" and "forecast errors case")

		Strategy S3 (no forecast errors)	Strategy S3 (forecast errors)
Total profit per week	Winter week	−12,825.0 €	−12,840.0 €
	Week in the transitional period	−5,963.5 €	−5,968.0 €
	Summer week	−82.08 €	−157.0 €

In the cases of the system operation in the winter week and week in the transitional period the overall losses per week are less than 1% higher than in the "ideal cases". In the summer week the overall loss increases by 90% relative to the "ideal case". However, the absolute overall loss increase in the summer week is approximately equal to the overall loss increase in the winter week. Finally, it can be concluded that strategy S3 can provide the cost-efficient system operation in spite of the forecast uncertainty.

Conclusion

In this work, several strategies for micro-grid operation in grid-connected mode were proposed and compared on the hypothetical residential micro-grid. The first strategy (S1) in addition to the optimization technique uses additional rule while the others are based on the mixed integer linear programming. To investigate the influence of the prediction horizon length on the operation cost-efficiency, third strategy uses mixed integer linear programming coupled with some elements of the model based predictive control approach. The optimization models were established and solved by Matlab, and comparison of the all proposed strategies was carried out for the each typical period of a year. The results indicate that taking into account predicted data on the demand and renewable generation when making decision on the system operation at current time step may considerable increase overall operation efficiency, even if there are certain errors in the forecasts of demand and renewable generation.

Nomenclature

- ED_k – electrical energy consumption at time step k, [kWh]
- EE_k – exchanged energy with external grid at time step k, [kWh]
- $EG_{2.k}$ – electrical energy production of CHP unit at time step k, [kWh]
- $EG_{2.k}^{\max}$ – maximum possible electrical energy production of CHP at time step k, [kWh]
- $EG_{2.k}^{\min}$ – minimum possible electrical energy production of CHP at time step, [kWh]
- ER_k – energy produced by photovoltaic modules, [kWh]
- e_k – electricity price at time step k, [€]
- g_k – natural gas price, [€]
- HD_k – thermal energy consumption at time step k, [kWh]
- $HG_{1.k}$ – thermal energy production from auxiliary boiler at time step k, [kWh]
- $HG_{1.k}^{\min}$ – minimum possible thermal energy production of auxiliary boiler at time step k, [kWh]
- $HG_{2.k}$ – thermal energy production from auxiliary boiler at time step k, [kWh]
- $HG_{2.k}^{\max}$ – maximum possible thermal energy production of CHP at time step k, [kWh]
- $HG_{2.k}^{\min}$ – minimum possible thermal energy production of CHP at time step k, [kWh]
- HS_k – stored thermal energy at time step k, [kWh]
- $HS^{\max}$ – thermal storage system maximum capacity, [kWh]
- k – time step, [h]
- NP – length of the prediction horizon, [h]
- NS – length of the scheduling horizon, [h]
- P – number of controllable generators in the system, [–]
- p – index related to generators, $p \in P$, [–]
- R – real numbers, [–]
- X_k – binary variable at time step k, [–]
- $\eta_{\mathrm{T1.k}}$ – auxiliary boiler efficiency, [%]
- $\eta_{\mathrm{T2.k}}$ – thermal efficiency of CHP plant, [%]

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